Aluminum Conductor Composite Reinforced Technical Notebook (477 kcmil family)

Conductor & Accessory Testing

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Overview

With several regions of the world facing potentially severe shortcomings in transmission line infrastructure, 3M has developed a new, high-performance conductor material that can provide transmission capacities up to three times greater than those of existing systems. The high-performance 3M Brand Composite Conductor, also known as Aluminum Conductor Composite Reinforced (ACCR), represents the first major change in overhead conductors since the conventional aluminum-steel reinforced conductor (ACSR) was introduced in the early 20th century.

Relying on a core of aluminum composite wires surrounded by temperature-resistant aluminum-zirconium wires, the 3M Composite Conductor can be installed quickly as a replacement conductor, with little or no modifications to existing towers or foundations. With its additional capacity and increased efficiency, the 3M Composite Conductor can upgrade transmission capacity with minimal environmental impacts.

Composite conductors can be used to upgrade existing transmission lines without modifying towers.

Benefits

The new conductor can help solve transmission bottlenecks, especially power flow restrictions concerned with operating lines at high temperatures. So, while this is not a total solution, it is believed this is an important part of a broad transmission grid solution. Due to its innovative design, the 3M Composite Conductor provides exceptional structural, mechanical, and electrical properties. A complete listing of properties is included in the Material Properties section of this document. Test results are included in the Conductor Test Data and Accessory Test Data sections. The enhanced properties translate into numerous benefits for utilities, including:

Increased Ampacity

The 3M Composite Conductor provides transmission capacity (ampacity) 1.5 to 3 times greater than conventional conductors, and with a lighter weight material. This enables line upgrades within existing right-of-way without significant tower modifications.

Decreased Congestion

With increased ampacity, the 3M Composite Conductor can relieve transmission congestion within a local region and provide greater flexibility when importing power from other regions. The congestion relief can translate into significant cost savings through reduced reliability-must-run (RMR) costs, increased independent power producer (IPP) output, and least-cost generation.

Reduced Environmental Impacts

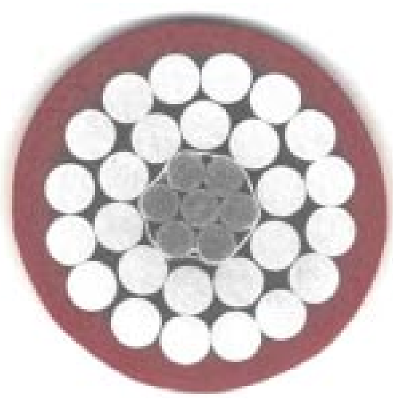
With the increased ampacity and lower weight of the 3M Composite Conductor, transmission lines can be upgraded without requiring line rerouting or tower modifications – construction activities which create environmental impacts.

Extended Tower Life

Because of its lower weight, a higher-ampacity 3M Composite Conductor can replace ACSR conductor without increasing tower loads. Due to the reduced thermal expansion, the Composite Conductor also meets sag limits without requiring new or modified towers. This extends the life of existing towers, which are typically a large capital asset of any transmission system.

Reduced Installation Time

The 3M Composite Conductor can be installed quickly without heavy construction equipment. This simple solution also reduces service interruption.



The 3M Composite Conductor relies on a core of aluminum composite wires surrounded by aluminum-zirconium strands.

Reduced Construction Costs

By avoiding tower modifications, it is possible to accomplish upgrades without extensive environmental studies, public hearings, and heavy construction operations.

Summary of Benefits

With its enhanced properties, the 3M Composite Conductor can address demanding applications such as transmission bottlenecks, thermal upgrades, difficult clearance requirements, increased ice-load ratings, river crossings, and other environmentally sensitive siting issues. Line rebuilds can be avoided where clearance requirements change or additional capacity is needed. With only aluminum constituents, the conductor can be used in high-corrosion locations. Where heavy ice loads exist, a smaller-diameter conductor can be used to achieve higher ice-load ratings without structure modifications. In new construction, long-span crossings can be achieved with shorter towers.

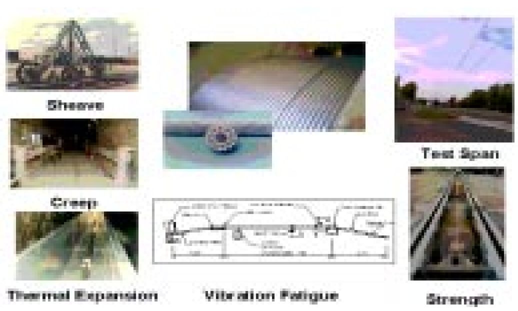
Building on Experience

A 3M-led team has successfully installed small- (477-kcmil) and medium-diameter (795-kcmil) ACCR conductors. In a cooperative agreement with the U.S. Dept. of Energy (DOE-Chicago), the team is further advancing the ACCR conductor by developing and testing medium- and large-diameter (795- to 1272-kcmil) ACCR and accessories on multi-span, high-voltage lines.

As the world leader in the manufacturing of metal matrix composite wire and high-strength aluminum-oxide fibers, 3M has forged a team of industry leaders, with a wealth of experience in the power transmission field. The additional team members include:

- Wire Rope Industries (WRI)
- Nexans
- Preformed Line Products (PLP)
- Alcoa Fujikura Ltd.
- The National Electric Energy Testing, Research and Applications Center (NEETRAC)
- Western Area Power Administration (WAPA)
- Oak Ridge National Laboratory (ORNL)

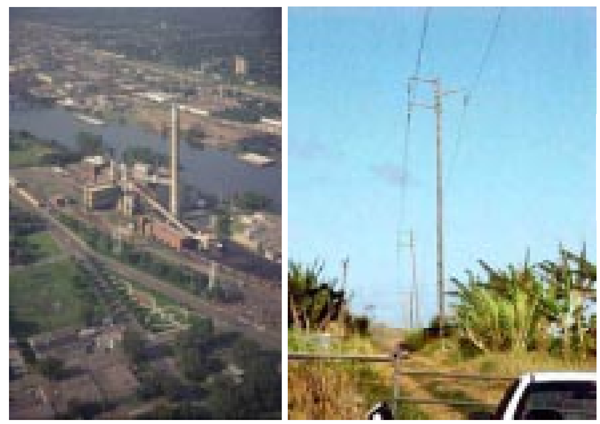
3M has done a variety of field and laboratory testing and has extensive data on the conductor and accessories. Composite conductors have been installed in several field locations, including a 115-kV line at Xcel Energy's Riverside Plant in Minnesota, a 46-kV line in Hawaii for Hawaiian Electric, and a 230-kV line in Fargo, North Dakota for WAPA.



Extensive laboratory testing has been performed with a variety of different tests passed.

Design Support

3M offers technical support resources and can work with you to tailor the 3M Composite Conductor to suit your needs. Our highly qualified engineers are available to answer your design questions and put our design experience and advanced design tools to work for you. In overhead power transmission, we have worked closely with customers to develop a wide variety of solutions. With customer interaction a key step in fully optimizing the conductor core, we can provide you with the expertise to successfully implement the 3M Composite Conductor, whether you simply need material properties or a complete design solution.



3M Composite Conductors have been Installed in several locations, including a 115-kV line at Xcel Energy's Riverside Plant in Minnesota (left), and a 46-kV line in Hawaii for Hawaiian Electric.

Using traditional installation methods, linemen install a span of 3M Composite Conductor on the 230-kV WAPA Network.

Material Properties

The 3M Composite Conductor is a non-homogeneous conductor consisting of high-temperature aluminum-zirconium strands covering a stranded core of fiber-reinforced composite wires. Both the composite core and the outer aluminum-zirconium (Al-Zr) strands contribute to the overall conductor strength.

Composite Core

The composite core contains 3M metal matrix composite wires with diameters ranging from 0.073" (1.9 mm) to 0.114" (2.9 mm). The core wires have the strength and stiffness of steel, but with much lower weight and higher conductivity. Each core wire contains many thousand, ultra-high-strength, micrometer-sized fibers. The fibers are continuous, oriented in the direction of the wire, and fully embedded within high-purity aluminum, as shown in Figure 1. Visually, the composite wires appear as traditional aluminum wires, but exhibit mechanical and physical properties far superior to those of aluminum and steel. For example, the composite wire provides nearly 8 times the strength of aluminum and 3 times the stiffness. It weighs less than half of an equivalent segment of steel, with greater conductivity and less than half the thermal expansion of steel, as shown in Table 1.

Table 1: Properties of Composite Core

Property	Value
Tensile Strength (min.)	200 ksi (1380 MPa)
Density	0.12 lbs/in^3 (3.33 g/cc)
Stiffness	31-33 Msi (215-230 GPa)
Conductivity	23-25% IACS
Thermal Expansion (20°C)	3.3 x 10^{-6} / °F (6 x 10^{-6} / °C)
Fatigue Resistance (Endurance)	> 10 million cycles at 100 ksi (690 MPa)
Emergency Use Temperature	> 570°F (300°C)

Table 2: Properties of Aluminum – Zirconium Wire

Property	Value
Tensile Strength (<0.153" diameter) [#] Tensile Strength (>0.153" diameter) [#]	>23.5 ksi (162 MPa) >23.0 ksi (159 MPa)
% Tensile Elongation[1]	> 2%
Tensile Strength Retention, 280°C/1hr [#]	> 90%
Density	0.097 lbs/in^3 (2.7 g/cm^3)
Conductivity / Resistivity at 20°C	>60%IACS <28.73 x 10^{-9} Ohm.m
Continuous use temperature	210°C
Emergency use temperature	240°C

[#] 10 in. (250 mm) gauge length

Source: *Properties of Heat-Resistant Aluminum-Alloy Conductors For Overhead Power-Transmission Lines*, K. Kawakami, M. Okuno, K. Ogawa, M. Miyauchi, and K. Yoshida, Furukawa Rev. (1991), (9), 81-85.

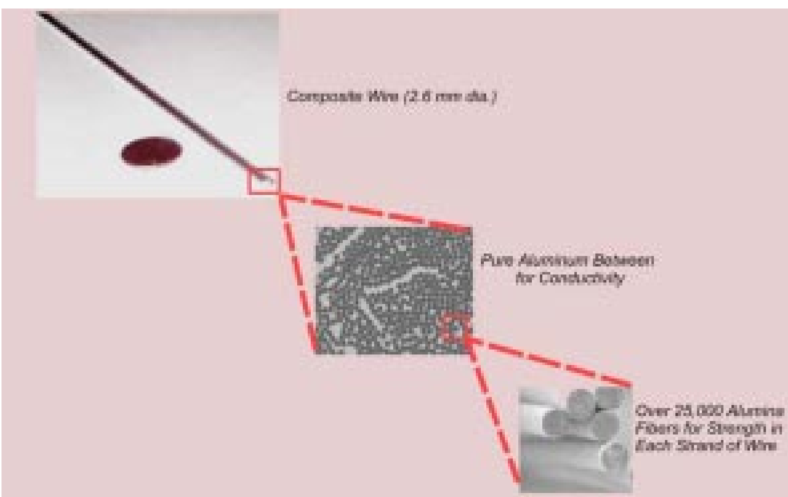


Figure 1: The composite wire provides high strength and conductivity at low weight.

Outer Strands

The outer strands are composed of a temperature-resistant aluminum-zirconium alloy which permits operation at high temperatures (210ºC continuous, 240ºC emergency), as shown in Figure 2. The Al-Zr alloy is a hard aluminum alloy with properties and hardness similar to those of standard 1350-H19 aluminum but a microstructure designed to maintain strength after operating at high temperatures; that is, it resists annealing. In contrast, 1350-H19 wire rapidly anneals and loses strength with excursions above 120–150ºC. The temperature-resistant Al-Zr alloy wire has equivalent tensile strengths and stress-strain behavior to standard 1350-H19 aluminum wire, as shown in Table 2.

Figure 2: The outer strands maintain strength after operating at high temperatures.

Properties of Standard Constructions

Standard constructions for 3M Composite Conductors range in diameter from 336 kcmil to 1,590 kcmil. Theoretical properties for these constructions are shown in the Tables 3 and 4. Table 3 displays the properties in English units; Table 4 shows metric units. Both tables cover type 13 and type 16 constructions, where *type* is the ratio of core area to aluminum area, expressed in percent. The stranding ratio represents the number of outer strands over the number of core wires. Following these tables, values of key properties obtained in actual field and laboratory tests are presented in the Conductor Test Data section. These summarize the behavior for the small size, 26/7, constructions.

Table 3: Typical Properties of 3M Composite Conductors (English Units)

Conductor Physical Properties													
Designation		336-T16	397-T16	477-T16	556-T16	636-T16	795-T16	954-T13	1033-T13	1113-T13	1272-T13	1351-T13	1590-T13
Stranding		26/7	26/7	26/7	26/7	26/19	26/19	54/19	54/19	54/19	54/19	54/19	54/19
kcmils	kcmil	336	397	477	556.5	636	795	954	1,033	1,113	1,272	1,351	1,590
Diameter													
indiv Core	in	0.088	0.096	0.105	0.114	0.073	0.082	0.080	0.083	0.086	0.092	0.095	0.103
indiv Al	in	0.114	0.124	0.135	0.146	0.156	0.175	0.133	0.138	0.144	0.153	0.158	0.172
Core	in	0.27	0.29	0.32	0.34	0.36	0.41	0.40	0.41	0.43	0.46	0.47	0.51
Total Diameter	in	0.72	0.78	0.86	0.93	0.99	1.11	1.20	1.24	1.29	1.38	1.42	1.54
Area													
Al	in^2	0.264	0.312	0.374	0.437	0.500	0.624	0.749	0.811	0.874	0.999	1.061	1.249
Total Area	in^2	0.307	0.363	0.435	0.508	0.579	0.724	0.844	0.914	0.985	1.126	1.195	1.407
Weight	lbs/linear ft	0.380	0.449	0.539	0.630	0.717	0.896	1.044	1.130	1.218	1.392	1.478	1.740
Breaking Load													
Core	lbs	8,204	9,695	11,632	13,583	14,843	18,556	17,716	19,183	20,669	23,622	25,089	29,527
Aluminum	lbs	5,773	6,704	7,844	9,160	10,248	12,578	15,041	16,287	17,548	20,055	21,301	25,069
Complete Cable	lbs	13,977	16,398	19,476	22,743	25,091	31,134	32,758	35,470	38,217	43,677	46,389	54,596
Modulus													
Core	Msi	31.4	31.4	31.4	31.4	31.4	31.4	31.4	31.4	31.4	31.4	31.4	31.4
Aluminum	Msi	8.0	8.0	8.0	8.0	8.0	7.4	8.0	8.0	8.0	8.0	8.0	8.0
Complete Cable	Msi	11.2	11.2	11.2	11.2	11.2	10.7	10.6	10.6	10.6	10.6	10.6	10.6
Thermal Elongation													
Core	10^-6/F	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Aluminum	10^-6/F	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
Complete Cable	10^-6/F	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
Heat Capacity													
Core	W-sec/ft-C	9	11	13	15	17	22	21	22	24	28	29	35
Aluminum	W-sec/ft-C	137	162	194	226	259	324	390	423	455	520	553	650

Conductor Electrical Properties													
Resistance													
DC @ 20C	ohms/mile	0.2597	0.2198	0.1832	0.1569	0.1375	0.1100	0.0933	0.0862	0.0800	0.0700	0.0659	0.0560
AC @ 25C	ohms/mile	0.2659	0.2250	0.1875	0.1606	0.1407	0.1126	0.0955	0.0882	0.0819	0.0717	0.0675	0.0573
AC @ 50C	ohms/mile	0.2922	0.2473	0.2061	0.1765	0.1547	0.1237	0.1050	0.0970	0.0900	0.0787	0.0741	0.0630
AC @ 75C	ohms/mile	0.3185	0.2695	0.2247	0.1924	0.1686	0.1349	0.1145	0.1057	0.0981	0.0858	0.0808	0.0687
Geometric Mean Radius	ft	0.0244	0.0265	0.0290	0.0313	0.0335	0.0375	0.0404	0.0420	0.0436	0.0466	0.0480	0.0521
Reactance (1 ft Spacing, 60hz)													
Inductive Xa	ohms/mile	0.4508	0.4407	0.4296	0.4202	0.4121	0.3986	0.3895	0.3847	0.3801	0.3720	0.3684	0.3585
Capacitive X'a	ohms/mile	0.1040	0.1015	0.0988	0.0965	0.0945	0.0912	0.0890	0.0878	0.0867	0.0847	0.0838	0.0814

Table 4: Typical Properties of 3M Composite Conductors (Metric Units)

Conductor Physical Properties

Designation		336-T16	397-T16	477-T16	556-T16	636-T16	795-T16	954-T13	1033-T13	1113-T13	1272-T13	1351-T13	1590-T13
Stranding		26/7	26/7	26/7	26/7	26/19	26/19	54/19	54/19	54/19	54/19	54/19	54/19
Diameter													
indiv Core	mm	2.2	2.4	2.7	2.9	1.9	2.1	2.0	2.1	2.2	2.3	2.4	2.6
indiv Al	mm	2.9	3.1	3.4	3.7	4.0	4.4	3.4	3.5	3.6	3.9	4.0	4.4
Core	mm	6.7	7.3	8.0	8.7	9.3	10.4	10.1	10.5	10.9	11.7	12.1	13.1
Total Diameter	mm	18.3	19.9	21.8	23.5	25.2	28.1	30.4	31.6	32.8	35.1	36.2	39.2
Area													
Al	mm^2	170	201	241	282	322	403	483	523	564	645	685	806
Total Area	mm^2	198	234	281	328	374	467	545	590	635	726	771	908
Weight	kg/m	0.566	0.669	0.802	0.937	1.067	1.333	1.553	1.682	1.812	2.071	2.200	2.589
Breaking Load													
Core	kN	36.5	43.1	51.7	60.4	66.0	82.5	78.8	85.3	91.9	105.1	111.6	131.3
Aluminum	kN	25.7	29.8	34.9	40.7	45.6	55.9	66.9	72.4	78.1	89.2	94.7	111.5
Complete Cable	kN	62.2	72.9	86.6	101.2	111.6	138.5	145.7	157.8	170.0	194.3	206.4	242.9
Modulus													
Core	GPa	216	216	216	216	216	216	216	216	216	216	216	216
Aluminum	GPa	55	55	55	55	55	51	55	55	55	55	55	55
Complete Cable	GPa	78	78	78	78	77	74	73	73	73	73	73	73
Thermal Elongation													
Core	10^-6/C	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Aluminum	10^-6/C	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Complete Cable	10^-6/C	16.5	16.5	16.5	16.5	16.6	16.3	17.5	17.5	17.5	17.5	17.5	17.5
Heat Capacity													
Core	W-sec/m-C	31	36	44	51	57	71	68	74	79	91	96	113
Aluminum	W-sec/m-C	449	530	636	743	849	1,062	1,280	1,386	1,494	1,707	1,813	2,134

Conductor Electrical Properties

Resistance													
DC @ 20C	ohms/km	0.1614	0.1366	0.1138	0.0975	0.0854	0.0683	0.0580	0.0535	0.0497	0.0435	0.0409	0.0348
AC @ 25C	ohms/km	0.1652	0.1398	0.1165	0.0998	0.0875	0.0700	0.0594	0.0548	0.0509	0.0445	0.0419	0.0356
AC @ 50C	ohms/km	0.1816	0.1536	0.1281	0.1097	0.0961	0.0769	0.0652	0.0603	0.0559	0.0489	0.0461	0.0391
AC @ 75C	ohms/km	0.1979	0.1675	0.1396	0.1195	0.1048	0.0838	0.0711	0.0657	0.0610	0.0533	0.0502	0.0427
Geometric Mean Radius	cm	0.7424	0.807	0.884	0.9552	1.021	1.1416	1.2302	1.2801	1.3288	1.4205	1.464	1.5882
Reactance (1 ft Spacing, 60hz)													
Inductive Xa	ohms/km	0.2817	0.2754	0.2685	0.2626	0.2576	0.2491	0.2434	0.2404	0.2376	0.2325	0.2302	0.2241
Capacitive X'a	ohms/km	0.065	0.0635	0.0618	0.0603	0.0591	0.057	0.0556	0.0549	0.0542	0.0529	0.0524	0.0509

Conductor Test Data

The 3M Composite Conductor has been tested in both laboratory and field conditions to verify theoretical properties and behavior. Testing to date has been performed on a standard 26/7 construction, 477-kcmil (281mm^2) conductor, along with an experimental 26/7, 284-kcmil (166 mm^2) conductor, the latter stranded with conventional 1350-H19 outer aluminum. Stranding of the 3M Composite Conductor uses conventional stranding equipment and conventional lay ratios for the aluminum, but longer lay ratios in the core section than found in conventional ACSR conductors. (The lay ratio is the ratio of the length of one helix revolution to the wire diameter.) The 284-kcmil conductor was stranded by Southwire, and the 477-kcmil conductor by Nexans.

Tests performed on the 477-kcmil conductor include:

- Tensile Strength
- Stress-Strain Behavior
- Creep

Tests performed on the 284-kcmil conductor include:

- Sag-Tension Behavior
- Ampacity-Temperature Behavior
- Vibration Fatigue
- Thermal Expansion
- Electrical Resistance

Figure 3: A field test span was installed at EDF, Les Renardières, France. Closeups show tower with instrumentation and termination wedge clamps.

Test Span

A 235-m (770-ft) test span was installed in Les Renardières, France, at the Electricité De France (EDF) outdoor test facility, as shown in Figures 3 and 4. This test was used to evaluate a 26/7, 284-kcmil 3M Composite Conductor over a three-year period from 1997 to 2000. Thermo-mechanical tests were conducted in the field to determine sag-tension behavior and ampacity-temperature behavior; other tests were conducted in laboratory settings.

Installation of the test span proceeded without problems. The two support towers differed in elevation by 17.4 ft (5.30 m). Mechanical tension was measured using a dynamometer placed between the tower and the dead-end joint. Sag was monitored using a sag sensor placed in the middle of the span.

Several thermocouples were inserted in the external layer to measure the conductor temperature. Weather conditions were recorded through a meteorological unit placed in the middle of the span, which measured ambient temperature, wind speed and direction, solar radiation, and rainfall. Ampacity was measured at the feeder test loop and was continuously regulated and measured. Parameters were stored as mean values for periods of ten minutes under steady conditions, and under overload conditions, the average values were calculated for periods of one minute.

In addition to being used for electro-mechanical tests, the conductor remained in place through multiple seasons and survived a "Storm of the Century" with hurricane-force, 100 mile/hr (160 km/hr) winds.

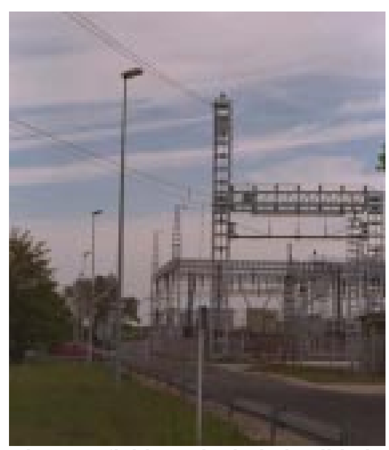


Figure 4: The EDF field test included validation of sag-tension and ampacity-temperature behavior.

Thermo-Mechanical Test Data

Ampacity tests were conducted on the test span to validate the 284-kcmil 3M Composite Conductor thermo-mechanical response under steady-state and severe transient peak conditions. The steady state and peak current conditions were:

- Steady state: 500 amps @70°C
- Transient 1: 800 amps @ 150°C
- Transient 2: 1000 amps @ 200°C

Tension, sag, and temperature were monitored in real time.

The test conditions were 19°C ambient temperature, light wind at 3.6 km/hr with a 30° angle from horizontal. Testing was done under a sun flux of 12.4 W/ft^2. It was assumed that the conductor emissivity was 0.6 and the solar absorption was 0.5. The applied current vs. time profile, and temperature response are shown in Figure 5.

Overall the results indicate the predictable and excellent performance of the 3M Composite Conductor at elevated temperature.

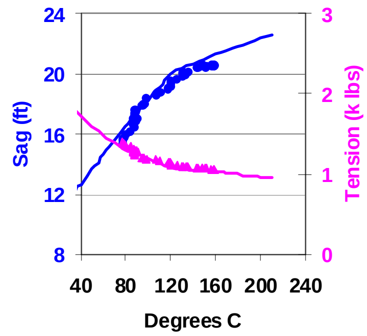


Figure 6: Sag-Tension Behavior in First Transient

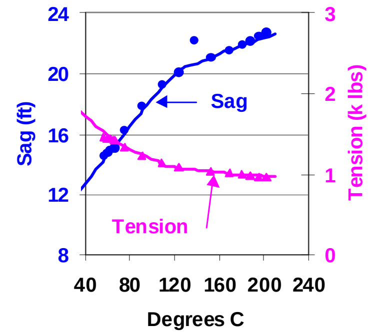


Figure 7: Sag-Tension Behavior in Second Transient

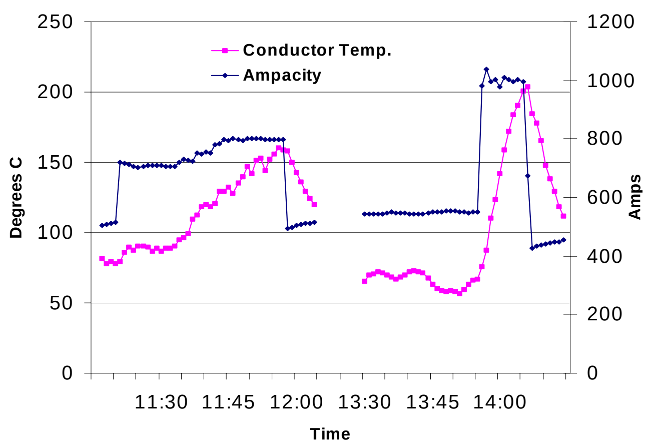


Figure 5: Test Conditions for Thermo-Mechanical Data

Sag-Tension Behavior

Sag data were collected under transient conditions and compared to the standard sag-tension model used by 3M for conductor design, such as that of Alcoa SAG10® computer software. The sag data in both transients (solid points on figures) validates the sag model (solid curves) at tension levels ranging from 1000 to 2500 pounds, as shown in Figures 6 and 7. The test span in this case was 235 meters (770 feet). The transition temperature was approximately 130°C. Indeed the model predicts the sag of the conductor by ± 0.3 inches (7.5 mm). A calculation using a calculated stress-strain curve for the composite core and standard curves (Alcoa) for the outer aluminum, found the compressive stress in the aluminum at the transition temperature to be 1.2ksi (8MPa).

Ampacity-Temperature Behavior

The rate of temperature change during the current transient is shown in Figure 8 and validates the Institute of Electrical and Electronic Engineers (IEEE) standard calculations for transient ampacity. These data have also been validated by CALITEM® computer software available from EDF.

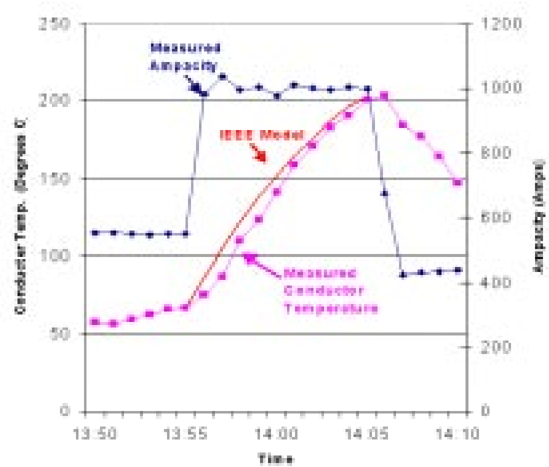


Figure 8: Ampacity and Temperature vs. Time

Tensile Strength

Three tensile tests were performed in laboratory settings with the ends of the 477-kcmil 3M Composite Conductor potted in epoxy, as shown in Figure 9. Two were performed at the National Electric Energy Testing, Research, and Applications Center (NEETRAC) using a short 3-ft (0.9-m) and long 19-ft (5.8-m) gauge length, and the other was tested at 3M facilities using a 10-ft (3-m) gauge length. Extreme care was taken during handling, cutting and end preparation to ensure individual wires did not slacken, as this could decrease strength values. The breaking load was then determined by pulling the conductor to a 1000-lb (4.4-kN) load and then loading to failure at 10,000 lbs/min (44 kN/min). As shown in Table 5, the breaking loads for all three tests exceeded the Rated Breaking Strength (RBS), which is 19,476 lbs (86.6 kN) for this construction.

Figure 9: A test bed was used to conduct stress-strain and tensile-strength measurements on a 477-kcmil conductor.

Table 5: Tensile Strength Tests

Test No.	Breaking Load, lbs (kN)	%RBS	Gage Length, ft (m)
1	20,400 (90.7)	105%	3 (0.9)
2	21,070 (93.7)	108%	19 (5.8)
3	21,040 (93.6)	108%	10 (3.0)

Stress-Strain Behavior

The stress-strain behavior of the 477-kcmil 3M Composite Conductor was determined in accordance with the 1999 Aluminum Association Standard entitled, "A Method of Stress-Strain Testing of Aluminum Conductor and ACSR." On the conductor, the test was started at 1000 lbs (4.4 kN) and the strain measurement set to zero. Load was then incrementally increased to 30%, 50%, 70%, and 75% of RBS, with the load relaxed to 1000 lbs between each increase. Finally, the conductor was pulled to destruction. A repeat test was performed on the core, loading to the same strains as measured in the conductor test.

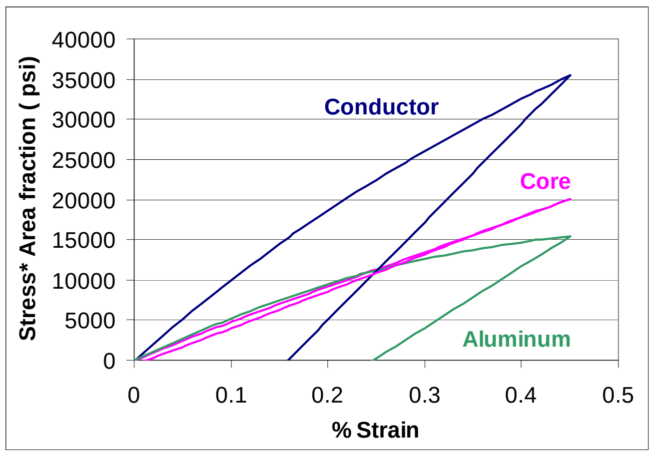


Figure 10:Stress vs. Strain Curves for 477-kcmil Conductor and Constituents

Curve fitting was applied per the Aluminum Association Standard, including derivation of the aluminum constituent. A set of curves without the creep addition for the 477-kcmil Composite Conductor and constituents is shown in Figure 10. In the graph, the core and aluminum curves are multiplied by their respective area fraction in the conductor.

Equations for Stress-Strain Curves

Conductor Initial:	Stress (psi) = $80{,}424*(\%Strain)^4 - 28{,}837*(\%Strain)^3 - 65{,}681*(\%Strain)^2 + 107{,}264*(\%Strain) - 114$
Conductor Final:	Stress (psi) = 122,125*(%Strain) – 19,432
Initial Elastic Modulus:	10,562,000 psi
Core Initial:	Stress (psi) = $-\ 607{,}851*(\%Strain)^4 + 853{,}573*(\%Strain)^3 - 392{,}529*(\%Strain)^2 + 378{,}608*(\%Strain) - 931$
Core Final:	Stress (psi) = 329,235 (%Strain) – 649
Aluminum Initial	Stress (psi) = $193{,}114*(\%Strain)^4 - 173{,}313*(\%Strain)^3 - 12{,}167*(\%Strain)^2 + 62{,}837*(\%Strain) + 20$
Aluminum Final	Stress (psi) = 88,215 (%Strain) – 18,707

NOTE: These equations are not normalized by the constituent area fraction

Based on the test results, the composite core is slightly stiffer than a comparative steel core for a 477 kcmil ACSR conductor, while the Al-Zr wires are quite similar to those of 1350-H19 aluminum. The resulting polynomial curves are corrected to pass through zero for the initial curves, and the final curves are translated to descend from 0.45% strain, as shown in the adjacent graph. The polynomial equations derived from the testing are shown in the box following the graph.

Sag10® computer software design coefficients are subsequently derived and shown in the Creep section.

Creep

Creep, a gradual deformation of a material under load, can occur when large loads are imposed on the conductor, such as during ice and snow storms. Creep measurements were conducted on the full conductor of the 477-kcmil 3M Composite Conductor at 20°C following the 1999 Aluminum Association Standard entitled, "A Method of Stress-Strain Testing of Aluminum Conductor and ACSR and A Test Method for Determining the Long Time Tensile Creep of Aluminum Conductors in Overhead Lines."

Four tests were performed, loading conductors to 15%, 20%, 25%, and 30% RBS. The strain was measured continuously for 1000 hours. Curves were fitted to the last 900 hours of data for each test load, resulting in an equation relating creep strain to time for each load. This permitted creep strain extrapolations to 6-month, 1-year, and 10-year creep times, as shown in Figure 11. Using the Aluminum Association Standard guideline, each of these extrapolated points was added to the initial stress-strain curve measured earlier, and plotted on a stress-strain graph. Polynomials were derived relating stress to strain for the given creep times. Estimated polynomial equations for the initial and final curves (after creep) are shown following the graph. The results show very little creep in the 3M Composite Conductor. Even for the 10-year extrapolation at 30% RBS, the conductor is expected to experience only 0.04% additional strain due to creep.

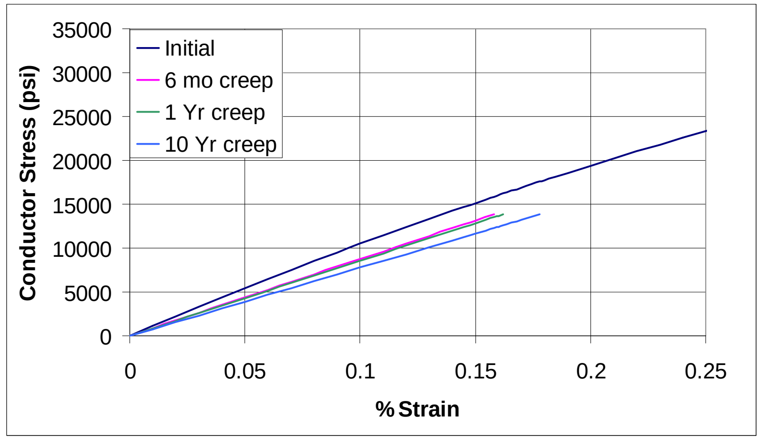


Figure 11: Stress vs. Creep-Induced Strain Curves for 477 kcmil Conductor, showing 6-Month, 1-Year, and 10-YearCreep

Equations for Creep Stress-Strain Curves

Conductor Initial:	Stress (psi) = $80{,}424(\%Strain)^4 - 28{,}837(\%Strain)^3 - 65{,}681(\%Strain)^2 + 107{,}264(\%Strain) - 114$
Initial + 6mo. Creep:	Stress (psi) = $87{,}584(\%Strain)$
Initial + 1 yr. creep	Stress (psi) = $85{,}595(\%Strain)$
Initial + 10 yr. creep	Stress (psi) = $77{,}643(\%Strain)$

Figure 12 is an additional graph that compares the creep of the 477 kcmil 3M Composite Conductor to an equivalent 477 kcmil ACSR calculated using Sag10® computer software. Two key points may be seen in the graph. First, the initial curve for the 3M Composite Conductor (ACCR) is always above the ACSR, illustrating the stiffer behavior. Second, the creep of the 3M Composite Conductor for 10 years at 30%RBS is much less than for ACSR. The additional creep strain for ACSR is approximately 0.10%, whereas the 3M Composite Conductor is less than half this value, 0.04%. Thus the 3M Composite Conductor provides outstanding creep resistance.

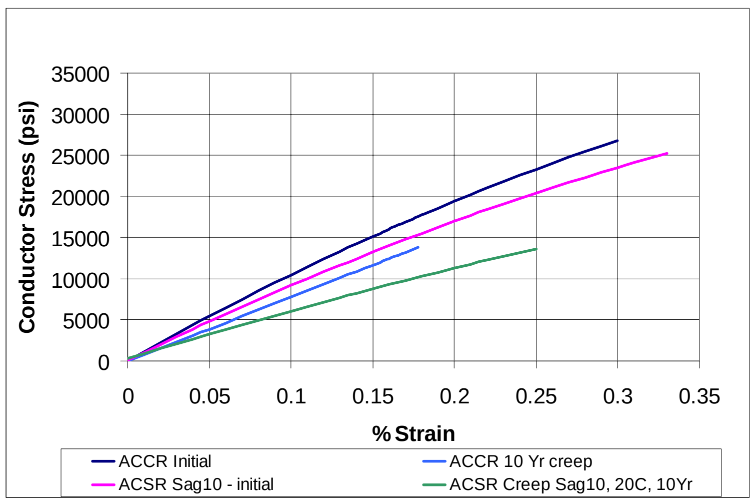


Figure 12: Stress vs. Strain curves, showing reduced 10-year creep of ACCR in comparison to ACSR.

Derived design coefficients for input into Sag10® computer software are shown in Table 6.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
17	53996	-10455	-148929	165944	75865	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	25963	-3374	135876	-292137	0.00128		
C0	C1	C2	C3	C4	CF		Core
-131	53268	-55226	120092	-85520	46093		
D0	D1	D2	D3	D4	α (core)		10 yr creep
-131	53268	-55226	120092	-85520	0.000353		

Table 6: Sag10® Computer Software Design Coefficients

Creep at Elevated Temperature

This represents a new type of test for overhead conductors. Since there is no precedent, or even a standard procedure for creep testing at high temperature, a single temperature (250°C) and load (15%RBS) were chosen to reflect the most severe conditions imagined to be possible. The test was then adapted using the spirit of the Aluminum Association Standard for room temperature creep testing.

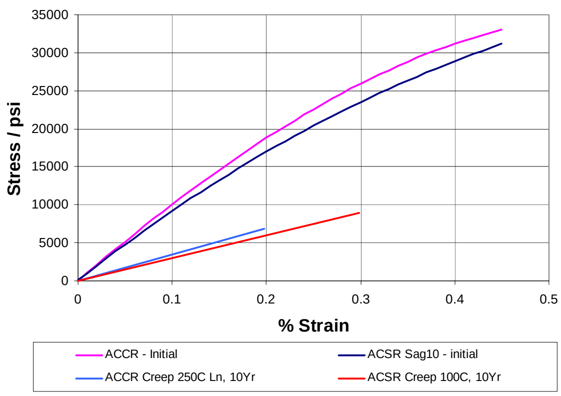


Figure 13. Comparison of ACSR and ACCR at elevated temperature.

The 477 kcmil Composite Conductor showed 0.08% creep after 1000 hours at 250°C, although significant noise from temperature fluctuations made this a difficult curve fit. The core was subject to a similar and separate test, and exhibited less than 0.006% strain in 1000 hours. Unstranded core wires would typically reach a zero creep regime, whereas in this test with a stranded conductor, a zero creep regime does not appear to be reached. Thus the measurement system may be contributing to some extra strain. A comparison to ACSR was made using data at 100°C. This is shown in Figure 13, which uses 10-year extrapolations. ACSR creeps approximately 0.2% in 10 years at 100°C and 15%RBS. For ACCR the 10-year creep at 250°C is approximately 0.15%. It is important to use this data in a sensible manner, and designing for 10 years at 250°C and 15%RBS is clearly not sensible. The emergency condition for ACCR is 240°C, and using 1000 hours at 15%RBS would be considered an aggressive condition. Thus < 0.1% creep is indicated which is acceptable.

Vibration Fatigue

Vibration fatigue tests were conducted on a 284-kcmil Composite Conductor at the University of Laval, Canada, under direction from EDF. Imposed peak-to-peak, vibration amplitudes were varied between 0.028-0.055” (0.7-1.4 mm), and controlled and recorded at a distance of 3.5” (89 mm) from the last contact with a suspension clamp. The tests were conducted at 25% of the rated breaking strength, and a turning angle of 5º. A schematic diagram of the test apparatus is shown in Figure 14. The active vibrating span was 23 ft (7m). This type of cap-and-groove suspension clamp is not recommended for 3M Composite Conductors, as it has too sharp a radius and is too rigid; however, it provides an excellent way to enforce and study the effects of a severe vibration condition. Third and fifth vibration modes were chosen for testing.

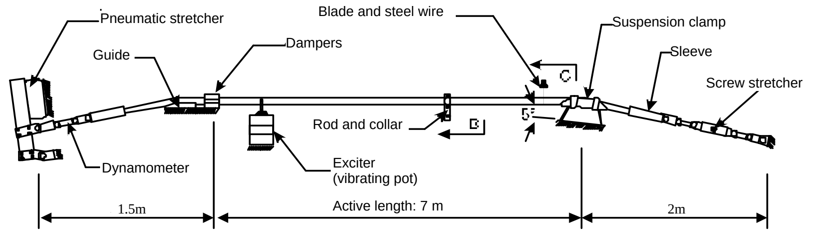


Figure 14: Vibration fatigue tests were conducted on a 284-kcmil conductor.

Table 7: Vibration Fatigue Tests

Test No.	Amplitude, inches (mm)	Amplitude antinode, inches (mm)	Frequency (Hz)	Cycles (Millions)	Ruptures (#)
1	0.028 (0.7)	0.34 (8.6)	54.5	104	0
2	0.039 (1.0)	0.48 (12.2)	54.0	8	2
3	0.055 (1.4)	0.85 (21.5)	34.0	3.1	4

The results indicate that the conductor fatigue life was far better than an equivalent all-aluminum conductor. A summary of the data is shown in Table 7. The endurance limit for this conductor was estimated as 100 million cycles at an amplitude of 0.028”−0.034” (0.7−0.85 mm). The graph in Figure 15 shows the onset of aluminum strand failures as a function of amplitude and vibration cycles. At 0.028” (0.7 mm) amplitude, there was no failure in the Composite Conductor at 104,000,000 cycles.

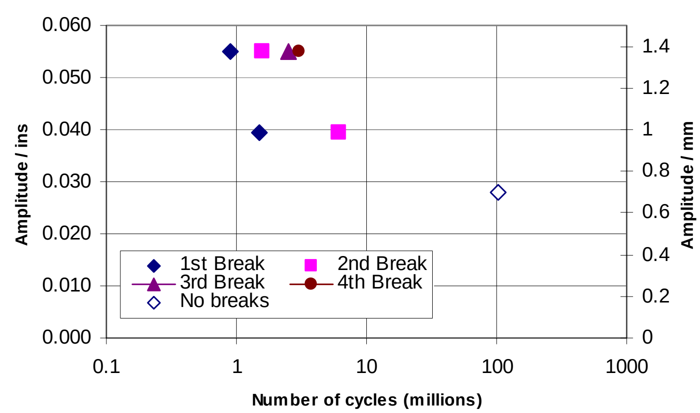
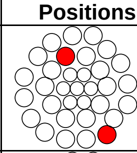
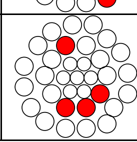


Figure 15: Amplitude and Number of Cycles to Produce Vibration Failure

The aluminum wires always failed before the composite wires, because the composite core wires have a far superior resistance to fatigue when compared to aluminum, and their fatigue resistance is equivalent to that of the steel wires found in ACSR. The failure of the aluminum strands was always in a region inside the suspension clamp, within 0.8” (20 mm) of the last point of contact. None of the aluminum strand failures were triggered by contact with the core, as shown in Table 8.

Table 8: Vibration Failure Summary

Amplitude (mm)	Rupture Positions	Rupture Initiation Site
1		Outer strand – contact mark with clamp body. Inner strand – fretting mark with outer layer.
1.4		All four in inner layer. 3 of 4, at fretting mark with outer layer. 1 of 4, at contact line with aluminum in same layer.

Even with the excellent fatigue behavior, vibration dampers are still recommended whenever possible, as shown in the “Accessory Test Data” section of this document. Dampers provide an easy and inexpensive way to protect this high-performance conductor.

Thermal Expansion

The coefficient of thermal expansion (CTE) was measured on a 15-foot-long 284-kcmil 3M Composite Conductor, as shown in Figures 16 and 17. A 5700-lb pretension

Figure 16: Thermal Expansion test frame at EDF, France.

(58% RBS) was applied for 72 hours to limit expansion by creep. The load applied during the test was 2250 lbs (22% RBS).

The temperature was increased incrementally between 20°C and 100°C and the thermal strain was measured after stabilization, as a function of temperature.

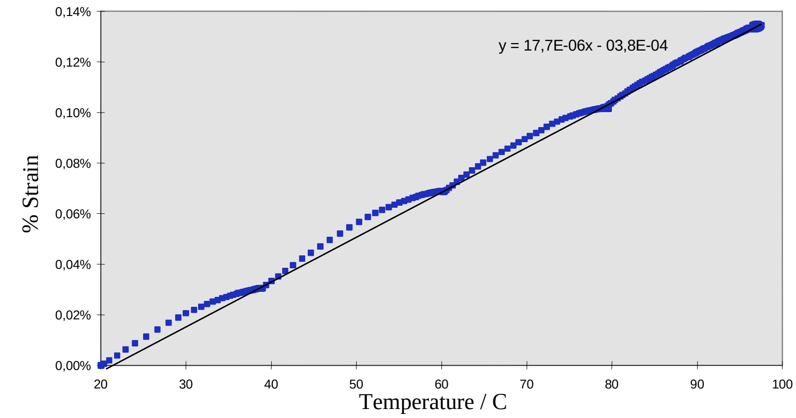


Figure 18: Thermal Strain vs. Temperature with line fit through hold temperatures. Slope of this line is the coefficient of thermal expansion.

Table 9: Thermal Elongation (10^{-6} °C^{-1})

	Measured	Predicted
Below Transition Temp (<130°C)	17.7	17.7
Above Transition Temp (>130°C)	N/A	6.3

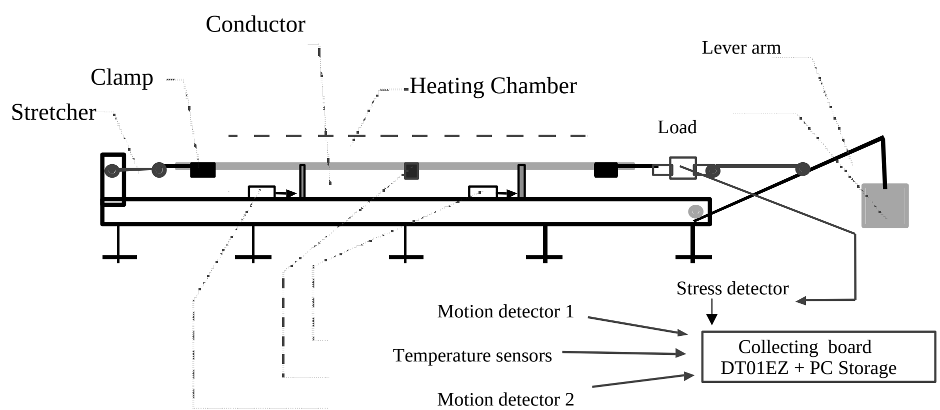


Figure 17: A schematic diagram of the test apparatus devised to study thermal expansion.

Electrical Resistance

The electrical resistance of the (26/7), 284kcmil 3M Composite Conductor was measured and compared with the calculated resistance, as shown in Table 10. The results were in excellent agreement and validated the predicted values.

As shown in Figure 18 and Table 9, the thermal expansion for the 284-kcmil conductor was measured as 17.7 x 10-6 / °C. This exactly matches the theoretical value computed from the constituent properties. The results followed the predictions from the CTE of each constituent up to 100°C. At high temperature, above the transition point of 130°C, the thermal expansion was not measured, but is anticipated to drop to very low levels. The core wire dominates the expansion at these temperatures and greatly limits the sag of the conductor.

Table 10: Resistivity and Resistance

Property	Value
Resistivity, ρ (aluminum wire) [1]	28.2 x 10^{-9} ohm-m
Resistivity, ρ (composite wire) [2]	50.8 x 10^{-9} ohm-m
Measured conductor resistance	0.185 ohm/km
Calculated conductor resistance	0.183 ohm/km

[1] ASM Handbook value for 1350-H19 wire
[2] 3M data

Axial Impact Strength

This test is usually employed to investigate slippage in conductor terminations. However, given the different nature of the ACCR core material, this test helps investigate whether, high shock loads (>100% RBS) could be sustained by the 477-kcmil Composite Conductor under high rate axial loading. The shock load may be comparable to loading rates experienced during ice jumps, galloping events, and impact from storm-blown objects. The test is performed in a similar manner to a tensile test, except the sample is suspended vertically and load is applied by dropping a 1300 lb weight from an elevation twelve feet above the sample (Figure 19).

Figure 19: Impact –test tower

Impact velocity is 24ft/sec, with an initial nominal pre-tension of 400 lbs. The sample is pulled to nominal tension at the bottom using a fabric strap fitted to a steel bar through an eye at the end of a PLP helical rod dead-end. A load cell measures the applied impact load and the data is recorded as a graph of load vs. time (Figure 20). The first peak shows when the core failed at a load of 22,284 lbs (114% RBS), with failure near the middle of the gauge section. A separate data flow device recorded a second peak related to rupture of the aluminum layers at a load of 17,854 lbs. Total failure occurred in 0.01 seconds, and the energy absorbed during failure was 3695 ft-lbs. There was no evidence of slipping or damage to the helical rod dead-end. Since failure is well above 100% RBS, this shows the conductor to have a positive strain-rate effect, and thus would not anticipate field problems due to shock loads.

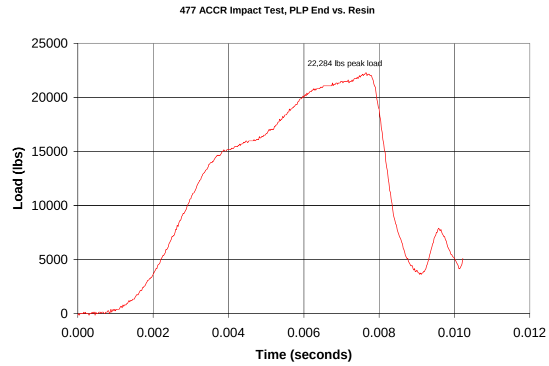


Figure 20: Load vs. time for Impact test

Crush Strength

A crush test on the 477 kcmil Composite Conductor is used to simulate possible damage during shipping and installation, such as a line truck running over a conductor. This applies loads similar to that stipulated in IEEE 1138. A section of conductor was crushed between two 6 inch steel platens. Load was held at 756 lbs (126lbs/linear inch) for one minute and then released. Visual inspection showed surface marks but no detectable deformation or other damage. All the aluminum and core strands were subsequently disassembled and tensile tested, and exhibited full strength retention.

Torsional Ductility

This test evaluates how well the 477 kcmil Composite Conductor tolerates twisting loads that can occur during installation. Resin end-fittings were applied to a length of conductor. One end is connected to a load actuator and other to a steel link, connected to a swivel bearing. The conductor was loaded to 25% RBS (4870 lbs) and then rotated in increasing steps of ±180 degrees until strand breaks were observed.

Eleven full positive rotations (3976 degrees) were required before the outer aluminum layer strands began to break. This is 0.68 rotations per foot. Before any strands broke, the aluminum became highly bird-caged upon returning to the zero rotation position (Figure 21). To fail the core, the outer aluminum strands were removed, and then further rotations applied. The inner aluminum strands bird-caged so all the load was on the core. It required 16 full rotations to fail the core wires. This is one (1) rotation per foot.

Thus it is anticipated torsion loading will not cause problems that are any more severe than with AAC (All Aluminum Conductor) and ACSR conductors, since the aluminum outer layer fails first. The torque required to reach the torsion limit was very large, suggesting it is beyond any realistic field or construction load.

Short Circuit Behavior

This test compared the behavior of the 477 kcmil Composite Conductor with a 477 "Hawk" ACSR conductor. Conductors were mechanically and electrically linked in series, and held under a tension of 10% RBS by helical rod distribution grips. This ensured the same mechanical tension and short-circuit current. Current was applied through compression terminations outboard of pulling grips. From initial temperatures of 40°C, the conductor was subject to a current (I) applied over a time (t), with the range of RMS current settings 31-35,000 Amps (74-84,000 Amps peak), and time durations of 0.2-1.0 seconds. The short circuit condition is quantified by a value of I^2t, ranging from 200-1200 kA^2s, by manipulation of both I and t. Measurement of the temperature rise of the conductors was taken from thermocouple locations; (i) between core wires, (ii) between core and aluminum wires, and (iii) between surface aluminum wires. The goal was to increase the short circuit condition until either the temperature reached 340°C or some physical limitation was reached (e.g. birdcage).

Figure 22 shows the maximum temperatures reached as a function of I^2t, with the starting temperature always being 40°C. Both the core and the surface aluminum strands ran cooler in ACCR than in ACSR. At 1200 kA^2s, where the temperatures reached 300-360°C, the ACCR always ran at a lower temperature by an average of 11°C at the core, 48°C at the aluminum/core interface, and 25°C at the surface. The surface to core difference was also lower in

Figure 21. :Highly birdcaged outer aluminum strands after returning to zero position from a rotation of 3970 degrees.

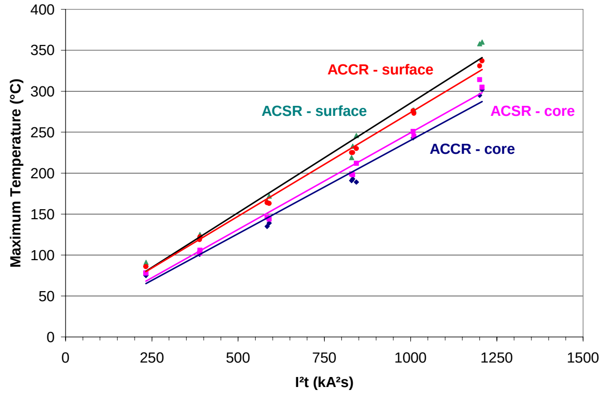


Figure 22: Maximum temperature rise vs. I^2t for surface and core locations in both ACCR and ACSR

ACCR (35°C) versus ACSR (50°C). The test was finally stopped at 1200 kA2s, due to bird-caging of aluminum layers in both conductors. ACCR exhibited a mild and reversible birdcage at 1000 kA^2s, and a permanent, non-reversible birdcage at 1200 kA^2s (Figure 23). ACSR only exhibited a mild and reversible birdcage at 1200 kA^2s. Thus the lower CTE of the ACCR core seems to slightly lower the temperature at which the birdcage appears. Overall, the behavior of ACCR appears to be satisfactory.

Figure 23: Birdcage in ACCR at 1200 kA^2s (300-340°C)

Lightning Resistance

A comparative test was performed between 477 kcmil Composite Conductor and ACSR of similar construction. A lightning arc was struck across a 6in (15cm) gap between an arc-head electrode and a 12m (40ft) long conductor strung at 15%RBS. Increasing charge levels were delivered to the conductor ranging from 50 coulombs (mild to moderate strike) to 200 coulombs (very severe strike). Typical currents were 100-400 amps with durations of 200-500 ms. Comparisons were made between degree of strand damage for different conductors and charge levels. Figure 24 shows the visual damage for ACCR and ACSR conductors. Damage was generally of three kinds; individual strand breaks, "splatter" of aluminum, or melted strands. These could occur on multiple wires and as is typical of lightning hits, there is substantial scatter in the number of affected wires for the same strike condition. Most importantly, the damage was always restricted to the outer aluminum layers. The type and amount of damage seemed to be similar for both ACCR and ACSR, and appeared to increase with increased charge level (Figure 25). Thus it appears the ACCR has a similar Lightning Strike Resistance to ACSR.

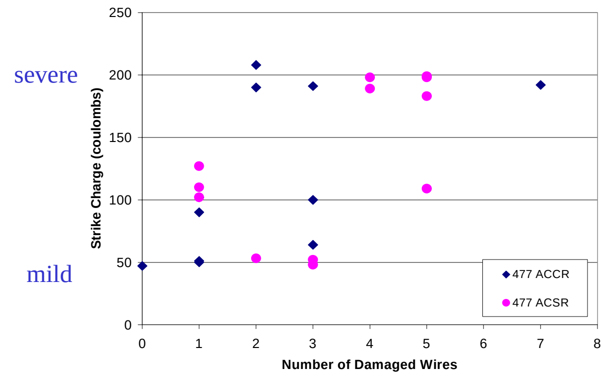
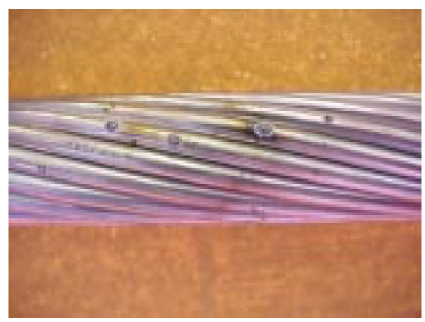


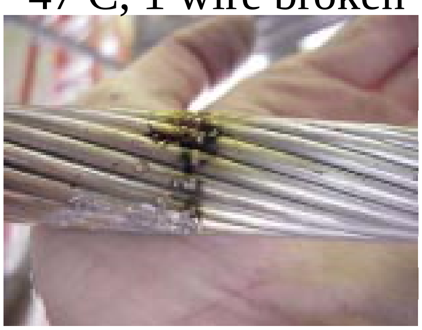
Figure 25: Coulomb (C) charge vs. number of damaged wires. The number of damaged wires increases with charge level, with little difference between conductor types.

ACCR **ACSR**

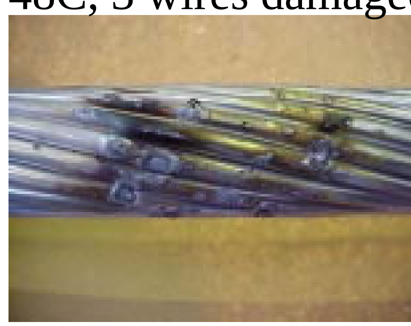
47 C, 1 wire broken



48C, 3 wires damaged



192 C, 6 wires damaged



199C, 5 wires damaged

Figure 24: Comparison of damage to outer aluminum wires of both ACCR and ACSR at different coulomb (C) charge levels

Accessory Test Data

As with conventional conductors, a variety of accessories are needed for successful operation of composite conductors. 3M has undertaken a thorough series of tests on accessories, in partnership with accessory suppliers.

Terminations and Joints

Terminations (also called dead-ends) and joints (also called mid-span splices or full-tension splices/joints) are commercially available from Preformed Line Products (PLP), and from Alcoa-Fujikura Ltd. Both companies furnished terminations used in these tests. Data are shown for the development of hardware for a 477-kcmil 3M Composite Conductor. Terminations and joints are available in two general types: compression and helical rod.

Compression-Type Hardware

The compression-type hardware from Alcoa-Fujikura uses a modified two-part approach for separate gripping of the core and then an outer sleeve to grip the aluminum strands, as shown in Figure 26. This approach is similar to the approach used in ACSS, although modified to prevent crushing, notching, or bending of the core wires. The gripping method ensures the core remains straight, to evenly load the wires, and also critically ensures that the outer aluminum strands suffer no lag in loading relative to the core. The hardware is rated for high-temperature operation.

Figure 26: Alcoa-Fujikura compression-type hardware.

Tensile Strength

Testing of compression dead-ends and joints from Alcoa-Fujikura, was performed with a gauge length of 10 ft (3.05 m). To test dead-ends, one end was terminated with the compression dead-end, and the other with an epoxy end-fitting. To test the joint, two conductor sections were joined using the joint, and then the two free ends were terminated with epoxy end-fittings. The samples were tested to failure in tension. Results are shown in Table 11, where the %RBS is based on an RBS of 19,476 lbs (86.6 kN), and the requirements for joints are to reach 95% RBS. Given the short gauge length used, this is a particularly good demonstration of the ability of the hardware to carry full load.

Table 11: Strength Data for Compression-type Dead-Ends and Joints

Load (lbs)	Load (kN)	% RBS	Failure Location	Hardware Type
20,340	90.5	104	Inside dead-end	Dead-end
19,860	88.3	102	Inside dead-end	Dead-end
20,860	92.8	107	At epoxy end	Dead-end
19,680	87.5	101	Inside dead-end	Dead-end
21,360	95.0	110	Inside dead-end	Dead-end
19,140	85.1	98.3	At epoxy end	Joint
19,380	86.2	99.5	At epoxy end	Joint
19,580	87.1	100.5	Inside Joint	Joint

Sustained Load

A sustained-load test was performed at 20°C following ANSI C119.4. A 19-ft-long (5.8 m) sample was terminated with a compression-style dead-end and an epoxy fitting, and then held under tension at 77%RBS (14,995 lbs) for 168 hours. Thereafter, the sample was unloaded and then pulled in tension to failure. The failure load was 20,620 lbs (106% RBS). This shows the dead-end adequately passes the sustained load requirement.

Additionally, a sustained-load test was performed on an 70-ft-long (21.3 m) sample, terminated with two epoxy fittings and a compression Joint/Splice in the center connecting two severed halves of conductor. This was then held under tension at 77%RBS (14,995 lbs) for 168 hours. Thereafter, the sample was unloaded and pulled in tension to failure. The failure load was 20,353 lbs (104%RBS). This shows the Joint adequately passes the sustained load requirement.

Elevated Temperature

A modified sustained load test was also performed at elevated temperature to verify the ability to carry load at the maximum temperature. Samples were run at 240°C for 168 hours under a tension of 15%RBS, after which the samples were pulled to failure at room temperature (20°C). The dead-end failed at 21,030 lbs (108% RBS) in the conductor gauge length and the joint at 20,320 lbs (104% RBS) in the conductor resin terminations. Thus full strength is achieved after a sustained load at elevated temperature.

Because the 3M Composite Conductor operates at high temperature, the temperature at which the hardware operates must be clearly understood, to prevent overheating of either the hardware or the conductor attachment points. A current cycle test was performed on the compression hardware and was based on the ANSI

C119.4 requirement. The major modification of the test was the temperature cycle, which was cycled between 30°C and a fixed high temperature of 240°C (which is the conductor emergency design condition). 500 cycles were performed, after which a further 100 cycles were run using a 30°C to 300°C cycle to simulate an overuse condition. The hardware evaluated included six different accessories, and these were:

Dead-ends

Terminal connectors

Joints/Splices

Jumper Connectors

Parallel Groove (PG) Clamps

Repair Sleeves

Data from the testing yielded information on the temperatures of the hardware components, the temperature stability, and the resistance stability as defined by ANSI C119.4. Overall, all the components passed the temperature and resistance stability requirements of the ANSI standard, even after the demanding cycling to

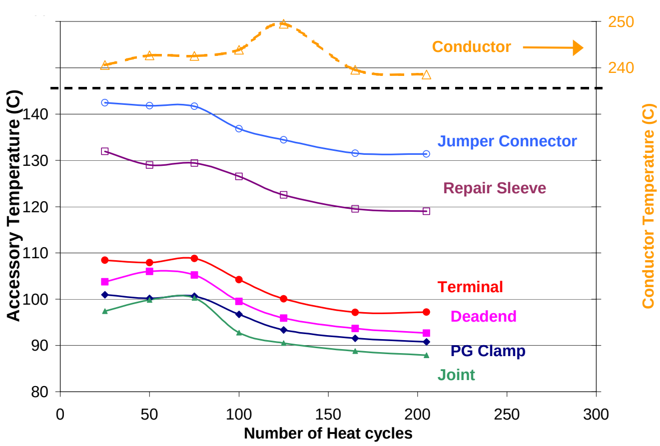


Figure 27: Temperatures of the Compression hardware with a 240°C conductor temperature.

300°C. Data is presented here for the first 200 cycles. Figure 27 shows the component temperatures when the conductor surface temperature is 240°C. The hardware which is subject to high mechanical loads (dead-ends and Joints), run at 90-110°C, which is well below the conductor temperature of 240°C. Since the hardware is made from 1100-O temper aluminum, the temperatures are acceptable. The other high mass hardware (PG Clamps, terminals) also run at similar temperatures. The thinner walled components such as the jumper connectors and repair sleeves run hotter, in the range 120-140°C, but this is acceptable given the low mechanical loads on these components.

Now the purpose of the cycle test is to look at the temperature stability and resistance stability to ensure no hot-spot develops due to electrical breakdown. For each component set, the average temperature difference from the conductor is calculated. To pass the test, the temperature excursion of any individual component at any time must not exceed 10°C from the average difference. All the components met the criterion for the entire test cycle. Table 12 shows the minimum and maximum excursions from the average difference (conductor – component) for the first 200 cycles. All components passed even after the 500 cycles and the extra 100 cycles at a higher temperature range.

	Cycles 25,50,75,100, 125,165,205		
	Mean	Mean Temp. Difference	
CONNECTOR	Temp(C)	Min. (C)	Max. (C)
Joint	99.3	5.7	7.4
PG Clamp	99.5	6.2	7.7
Dead-end	99.9	5.8	6.7
Terminal	103.8	3.5	7.7
Repair Sleeve	125.4	7.8	9.6
Jumper Connector	137.2	6.2	8.3
Conductor	242.5		

Table 12: Average component temperatures and maximum and minimum temperature excursion around the average temperature difference of conductor minus component.

A similar theme is followed for resistance, whereby the average resistance for each component during the run is calculated and then the deviation of any component around the average is studied. The requirement is that the resistance of any component at any time must be within 5% of the component average. Table 13 shows the data after 200 cycles, showing all components are well within the 5% criterion. The final data after 500 cycles and the additional 100 cycles at the higher temperature cycle, also demonstrated the components satisfactorily passed the required performance.

	Maximum deviation from mean resistance	
CONNECTOR	% Negative	% Positive
Joint	-1.21	1.30
PG Clamp	-1.42	1.91
Dead-end	-0.72	0.72
Terminal	-1.14	1.14
Repair Sleeve	-0.78	0.60
Jumper Connector	-0.93	1.23

Table 13: Maximum deviation of component resistances from the mean component resistance.

Helical Rod-Type Hardware

Helical rod-type hardware available from PLP, as shown in Figures 28 and 29, has been developed for use with the 3M Composite Conductor and for use at high operating temperatures. It uses the helical rod design which places minimal compression loading on the conductor. A multi-layer design maximizes both the holding strength and heat dissipation, and has the advantage of easy installation.

Table 14: Strength Data for Helical-Rod Dead-End and Joint Assemblies

Load (lbs)	Load (kN)	% RBS	Failure Location	Hardware Type
20,214	89.9	104	Mid-span	Dead-end
21,222	94.4	109	Mid-span	Dead-end
20,846	92.7	107	Mid-span	Dead-end
19,231	85.5	98.7	Mid-span	Joint

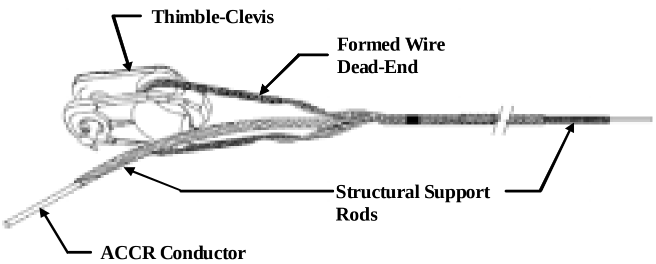


Figure 28: Helical-rod dead-end assembly

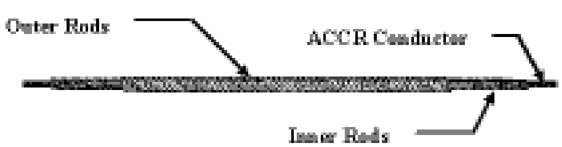


Figure 29: Helical-rod full-tension splice / joint assembly.

Tensile Strength

Tensile tests were performed using gauge lengths of 25 ft (7.6 m) terminated at both ends with dead-ends. To evaluate joints, the above test was cut in the center, and then re-connected using a splice. This demonstrated support for the full RBS of the conductor. Data are shown in Table 14 for the 477-kcmil 3M Composite Conductor, tested at room temperature. The %RBS is based on an RBS of 19,476 lbs (86.6 kN).

Sustained Load

Additionally, a sustained-load test was performed at 20°C following ANSI C119.4. A 30-ft-long (9.1 m) sample was terminated with two helical-rod dead-end assemblies, and then held under tension at 77%RBS (14,995 lbs) for 168 hours. Thereafter, the sample was pulled in tension to failure, as shown in Figures 30 and 31. The failure load was 20,480 lbs (105% RBS). This shows the dead-end adequately passes the sustained load requirement.

Figure 30: Testing of helical-rod splice to destruction in a tensile test.

An additional sustained load test was performed at elevated temperature. This test was conducted on a 55ft long sample, configured with a PLP helical rod dead-end at either end of the sample, and at mid-span was a PLP helical rod splice. The sample was held at 15% RBS and 240°C for 168 hours. The residual strength was measured thereafter at room temperature (20°C), and was found to be 20,666 lbs (106% RBS), and thus passes the test.

Figure 31: Tensile failure of conductor at >98% RBS during helical-rod splice strength test.

Elevated Temperature

As with compression-type hardware, the temperature differences within the termination and the attachment point must be clearly understood, to prevent overheating of either the termination or the conductor string. In the test, the conductor was heated to 242°C. Using embedded thermocouples, the temperature was monitored around the helical-rod dead-end assembly of a 477-kcmil Composite Conductor.

With the 3M Composite Conductor at 242°C, the inner helical rods of the termination reached 140°C, and attachment pin to the insulator string remained at approximately 27°C, as shown in Figure 32. The 140°C temperature was recorded on the inner rods where they extended beyond the outer dead-end rods (see Figure 28). However, the temperature of the inner rods beneath the outer dead-end rods was cooler, reaching only 100°C, due to the extra thermal mass. Thus the materials used at the termination would all be suitable for use with prolonged exposure to temperature.

A similar experiment was performed on a splice assembly. With the temperature of the conductor at nearly 200°C, both the inner and outer structural rods were running at less than 50°C, as shown in Figure 33.

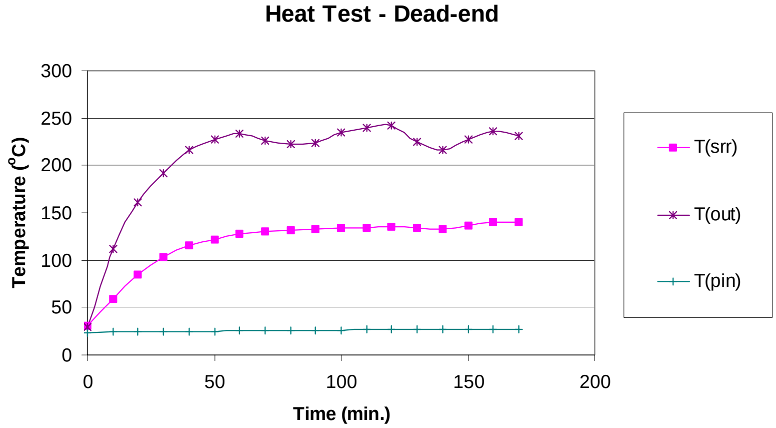


Figure 32: Graph of temperatures at a dead-end assembly showing conductor, rods and clevis temperatures.

High-Voltage Testing

Preliminary testing was conducted to determine radio influenced voltage (RIV) noise on a dead-end assembly. The ends of the helical rods had a standard "ball end" finish. No noise was detected up to 294 kV (phase-phase) for a single conductor.

Aeolian Vibration

Aeolian Vibration testing was performed on a dead-end and results are reported in a later section with Suspension Assemblies.

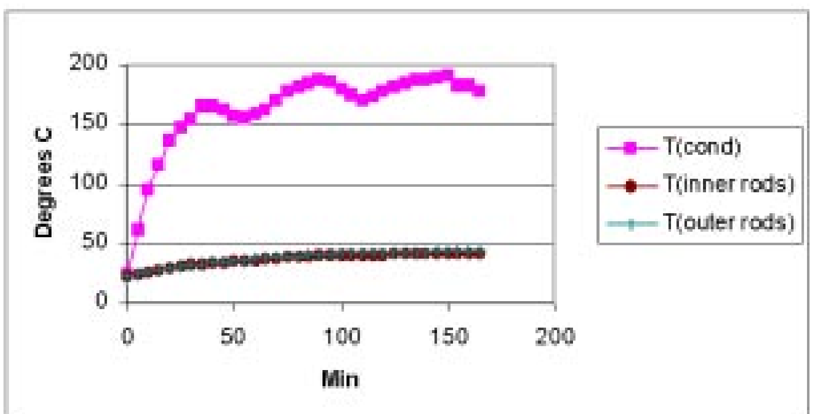


Figure 33: Graph of temperatures at a splice assembly showing conductor and rod temperatures.

Suspension Assemblies

Preformed Line Products (PLP) provided and tested suspension assemblies for the 3M Composite Conductor, as shown in Figure 34. These accessories are based on field-proven ARMOR-GRIP® Suspensions. The multi-layer design maximizes the mechanical protection and heat dissipation, while minimizing heat transferred to mating hardware and insulators. A cushioned insert provides protection against wind and ice loads. A suspension assembly is shown in the picture below. The helical rods also provide local stiffening to the conductor, which critically reduces the bending strains on the conductor core.

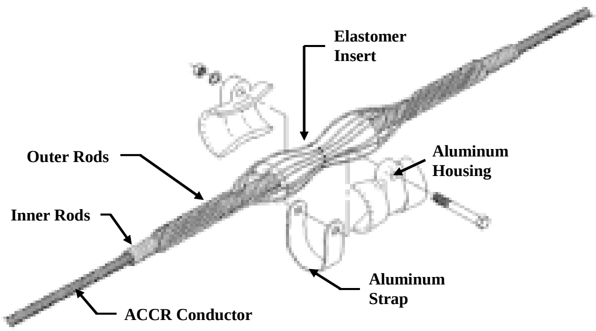


Figure 34: Helical-Rod Suspension Assembly from PLP.

Figure 35: Suspension in turning angle test holds 90% rated breaking load.

Turning Angle

Turning angle tests ensure the 3M Composite Conductor can carry high mechanical tensile loads (approaching the rated breaking load) through a 30° turning angle without failure in the bending region, as shown in Figure 35. For the 477-kcmil Composite Conductor, no damage or wire failures were reported at 90% RBS loading.

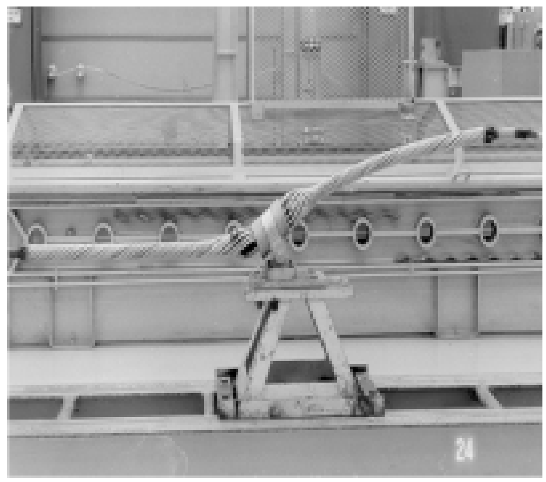


Figure 36: Unbalanced load test carried 10%RBS before slipping.

Unbalanced Load

Unbalanced load tests simulate situations where neighboring spans have very different loads, such as those due to ice accumulation. If the imbalance is too high the tower may be pulled down. To mitigate this, the suspension assembly is designed to allow the conductor to slip, which then changes the sags of the adjacent spans and permits more equal tensions on the spans. The goal is for the suspension assembly design to exhibit three modes of behavior with increasing horizontal loads: holding, partial slip, and continuous slip. In the test on a new, un-weathered 284-kcmil 3M Composite Conductor, the assembly is anchored and the conductor is pulled in an attempt to pull it through the assembly, as shown in Figure 36. The slip mode is shown in Table 15, and shows very satisfactory performance. All suspension assemblies are designed to carry at least 10% RBS.

Table 15: Slip Modes and Loads

Slip Mode	Load (lbs)
Holding	0 – 2150
Partial Slip	2150 – 3000
Continuous Slip	3000 +

Elevated Temperature

As with terminations and splices, the temperature differences between the conductor and the suspension assembly must be clearly understood to ensure the assembly retains its strength. In the test, the conductor was heated to 215°C. Using embedded thermocouples, the temperature was monitored around the suspension assembly of a 477 kcmil 3M Composite Conductor.

With the conductor at 215°C, the inner helical rods of the assembly reached 118°C, and the elastomer insert reached 36°C, as shown in Figure 37. The 118°C temperature was recorded on the inner rods where they extended beyond the outer suspension rods (see Figure 26). However, the temperature of the inner rods beneath the outer suspension rods was cooler, due to the extra thermal mass. Based on this temperature information, it is believed that these materials have sufficient durability to the temperature exposure with time.

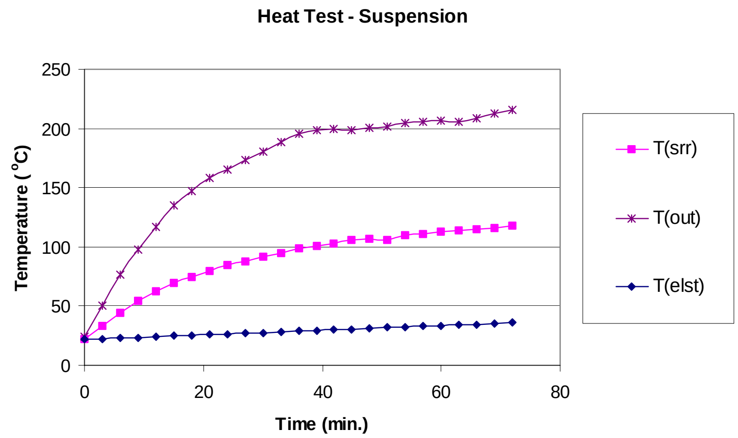


Figure 37: Graph of temperature vs. time for conductor, inner suspension rods, and elastomer, showing low temperature at elastomer."

Galloping

Galloping, a high-amplitude vibration that occurs in transmission lines under certain resonant conditions, was tested at PLP's facilities. In these tests the goal was to measure the endurance limit and to characterize any damage to the terminations and suspension hardware or conductor. A length of 477-kcmil Composite Conductor was terminated at each end using helical-rod dead-end assemblies with a helical rod suspension in the center, as shown in Figure 38. This produced two spans each of 82 ft (25m). The conductor was held under a constant tension. On one side, an actuator created low frequency vibrations and produced a maximum vibration amplitude of 39 inches (1m).

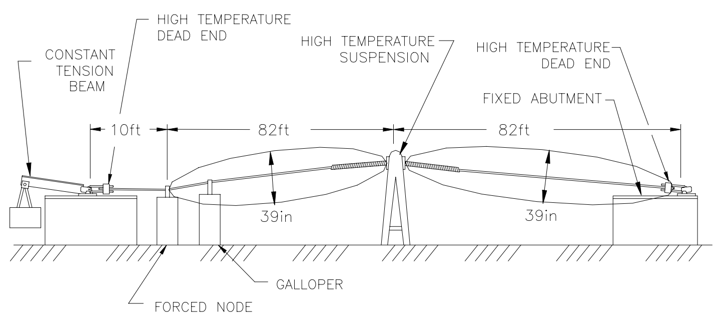


Figure 38: Schematic of the test setup to evaluate resistance to galloping of the helical-rod dead-end and suspension assemblies.

In the galloping test on a 477-kcmil Composite Conductor, 100,000 cycles were successfully completed with no damage to either the conductor or suspension hardware. The conductor was disassembled for visual inspection, which indicated no damage, and strength tests on the core wires showed full strength retention.

Aeolian Vibration

The purpose of this testing is to demonstrate that the conductor accessories will protect the 3M Composite Conductor when it is subjected to dynamic, wind induced bending stresses. Within the span itself, this vibration activity has little or no influence on the conductor. However, at the structures where the conductors are supported or dead-ended, this vibration activity produces bending stresses. The peak-to-peak amplitude of the vibration of the conductor in the span is generally less than the diameter of the conductor itself, but over a number of years, if not properly protected, the conductor can experience fatigue failures. Laboratory aeolian vibration testing at higher levels of activity is commonly used to demonstrate the effectiveness of accessories under controlled and accelerated conditions. The only published industry test specification for aeolian vibration testing is for vibration testing of Optical Ground Wire (OPGW). This specification is IEEE 1138 and is adopted for the testing of the 3M Composite Conductor.

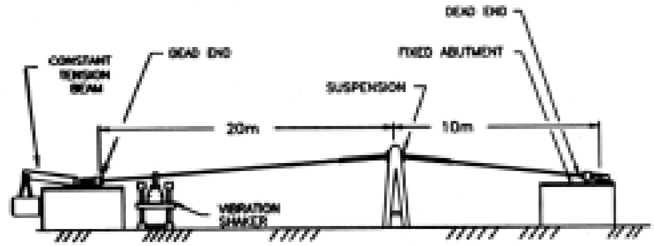


Figure 39: Aeolian Vibration Test Arrangement for suspension Assembly

Suspension Assembly

Using a vibration shaker (Figure 39), a 20m sub-span of 477 kcmil Composite Conductor was tensioned to 25% RBS (4857 lbs) using a beam/weight basket, and maintained at a vibration frequency of 38 hertz, with an amplitude of 0.29" peak-to-peak, (one-third of conductor diameter), for a period of 100 million cycles (30 days). Visual observations were made twice daily of the conductor and the Suspension Assembly during the test period. At the completion of the test period the Suspension Assembly was removed and carefully inspected for wear or other damage. The section of the conductor at the Support Assembly was cut out of the span and dissected to determine if any wear or damage had occurred to the Al-Zr outer strand, the aluminum tape or to the composite core. After 100 million cycles of severe aeolian vibration activity there was no wear or damage observed on the components of the Suspension Assembly, nor on the Al-Zr outer strands, nor on the composite core (see Figure 40 and Figure 41).

Figure 40: Outer Strands & Aluminum Tape After Aeolian Vibration Test

Figure 41: Core After Aeolian Vibration Test

Dead-end Assembly

Another aeolian vibration test was performed in which the Suspension Assembly has been removed to isolate the active vibration on the Dead-end Assembly. The active span was 30m tensioned to 25% RBS (4857 lbs), and maintained at a vibration frequency of 33 hertz, with an amplitude of 0.29" peak-to-peak, (one-third of conductor diameter), for a period of 100 million cycles (35 days). Again the same result was found after 100 million cycles, that with severe aeolian vibration activity there was no wear or damage observed on the components of the dead-end assembly, on the Al-Zr outer strands, nor on the composite core.

Dampers

Dampers, available from Alcoa-Fujikura, are used to reduce the vibration amplitude by absorbing a portion of the wind-induced energy, as shown in Figures 42 and 43. This results in a reduction of bending amplitudes near the conductor attachment points.

For 477-kcmil ACSR conductor, the recommended damper size is a 1705; however, the 3M Composite Conductor is adequately dampened with the smaller size 1704 damper, due to the lower conductor weight and associated lower conductor impedance. Damping efficiencies for both the 1704 and 1705 were measured and compared to the 15% and 26% acceptance curves, as shown in Figure 44. Dampers meeting or exceeding the 15% curve will provide adequate protection on 477-kcmil conductor. The 26% acceptance curve applies to larger diameter conductors and is shown for comparative information only.

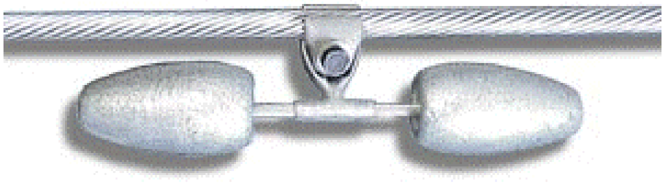


Figure 42: Damper from Alcoa-Fujikura.

Figure 43: Dampers were installed on the 477 kcmil 3M Composite Conductor at Xcel Energy's Riverside Plant.

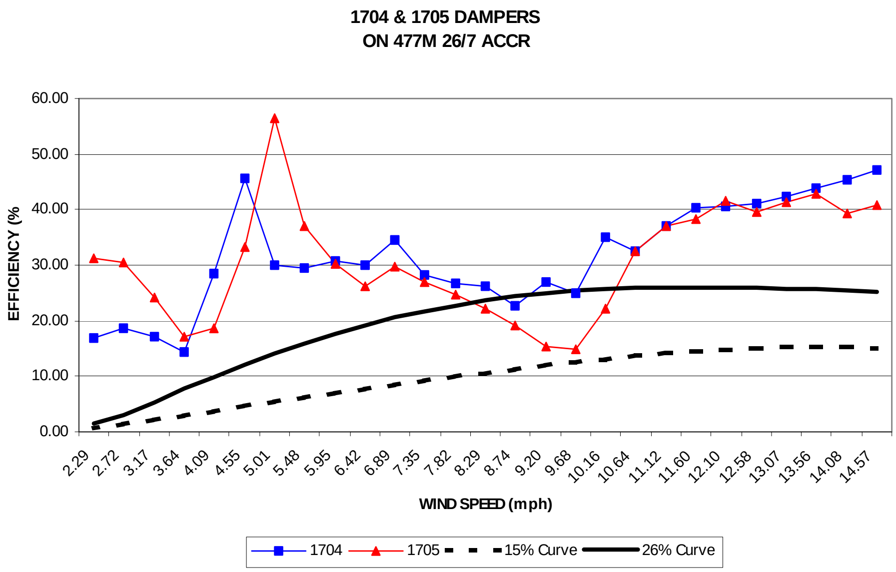


Figure 44: Efficiency vs. wind speed showing performance of two different damper sizes on 477 kcmil 3M Composite Conductor.

Sheaves (Stringing Blocks)

Standard stringing sheaves (or blocks) can be used during installation to minimize bending strain, but 3M recommends using lined blocks with a minimum diameter of 32*D*, where *D* is the ACCR conductor diameter. The 477-kcmil Composite Conductor has been successfully installed using 28-inch (71-cm) diameter sheaves.

Figure 45: Reciprocating cart used at EDF, to run the conductor over a sheave in the sheave test

Sheave Test

Simulation of an installation was done using a sheave (i.e., dolly) test that reproduces the passage of a conductor over multiple dollies during an installation, as shown in Figures 45 and 46. The conductor used was the 284-kcmil Composite Conductor. A suitable sheave diameter must be selected to avoid overstressing the conductor core. The chosen pulleys were 31 inches (79cm) in diameter with a 20^o angle between pulleys. The conductor was tensioned at 23% RBS, (i.e. 2246 lb, or 10.0 kN) and the length of conductor tested was 113 feet (34.4m). The cart shown below traveled 36 times along the conductor length at a speed of 6.6 ft/s (2m/s).

The conductor was tested in tension after the sheave test to measure the breaking load. It exhibited no reduction in strength, and confirmed the good behavior of the conductor for installation over sheaves.

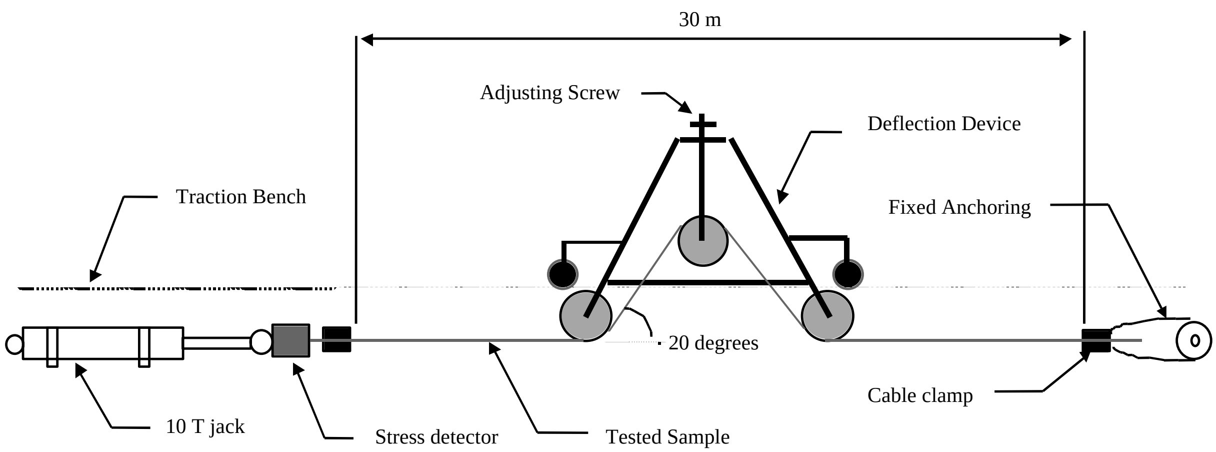


Figure 46 : Schematic of the sheave test setup.

Installation Guidelines

General

The 3M Composite Conductor has been installed in a variety of different places. One installation was on a short span of 477 kcmil Composite Conductor in Xcel Energy's 115kV system in Minneapolis to feed power from a power plant to the network, as shown in Figure 47. It replaces a conventional ACSR conductor to double the possible

Figure 47: Test Line installed at Xcel Energy feeds power from a power plant to the network.

ampacity while keeping the same clearance and tower loads. Hawaiian Electric installed 477 kcmil Composite Conductor on the North shore of the island of Oahu, on their 46kv network (Figure 48) taking advantage of the excellent corrosion resistance of the conductor.

Figure 48: 46kV installation at Hawaiian Electric on the North Shore of Oahu.

A section of 477 kcmil Composite Conductor was strung at a new outdoor test facility in Oak Ridge, TN (Figure 49). The line is highly instrumented, and will be used to study sag and tensions under high temperatures and severe thermal cycling conditions. Additionally 795 kcmil Composite Conductor was installed by WAPA on a 230kV line near Fargo, North Dakota (Figure 50). The conductor is well suited for the high ice loading and vibration conditions of the area.

Figure 49: 400 VDC outdoor test line installation at Oak Ridge, Tennessee.

Figure 50: 230 kv installation at WAPA situated near Fargo, North Dakota.

The installation of composite conductors basically follows IEEE 524, "Installation Guidelines for Overhead Transmission Conductors". However there are some additional requirements. Departures from the traditional equipment and procedures used for ACSR are summarized in Tables 16 and 17.

Installation Equipment	ACSR	ACCR
Stringing Blocks	Yes	Yes (28")
Bull Wheel	Yes	Yes (36")
Drum Puller	Yes	Yes
Sock Splice	Yes	Yes
Conductor Grips	Any	DG-Grips
Cable Spools	Yes	Yes (40" Drum)
Cable Cutter	Yes	Yes
Reel Stands	Yes	Yes
Grounding Clamps	Yes	Yes
Running Ground	Yes	Yes

Table 16: Comparison of installation equipment needs between ACSR and the 3M Composite Conductor (ACCR)

Installation Procedure	ACSR	ACCR
Cable Stringing	Tension / Slack	Tension
Sag Tensioning	Any	Line of sight, Dynometer
Dead Ending	Any	Use DG-Grip with chain hoists
Clipping	Any	Any

Table 17: Comparison of installation procedures between ACSR and the 3M Composite Conductor (ACCR)

Stringing Method

The recommended conductor stringing method is the "tension method." Bending of the composite conductor must be carefully monitored during installation to avoid damage to the composite core. The combination of bending and tensile loads can damage the core if they exceed the allowable core strength. The following sections include recommendations on use of conductor grips and stringing block diameters.

Sock Splice

During pulling through the blocks, a swivel should be used to minimize twisting of the conductor. A *sock splice*, also known as a basket grip, Chinese finger, Kellem grip, or wire mesh, can be used to pull composite conductors. An example of a sock splice can be found in the GREENLEE® catalog.

Conductor Grip

The preferred method for introducing tension into the conductor is to tension the conductor with a helical-rod DG Grip (Figure 51) that is removed after the sag procedure is completed. Rigid grips, such as Chicago Grips should never be used with this conductor because they cause damage. DG Grips are rated to carry 60% of the conductor RBS, and should only be used three times during installation for the purpose of gripping the

Figure 51 : Helical-rod DG-Grip (top) and dead-end(bottom) assemblies may be used as a conductor grip.

conductor. For cases where high tensions or high safety factors are required, Helical-rod dead-end assemblies may be used. These are specifically designed to carry the full load of the conductor without any potential damage to the conductor, as shown in Figure 51. To facilitate removal, the structural rods should not be snapped together at the end, when using the helical-rod assemblies as a conductor grip. A helical-rod dead-end should only be used once as a conductor grip and can be re-used as a permanent dead-end.

Stringing Block (Sheaves)

According to IEEE Std. 524, as sheave diameters are increased, several advantages are gained. First, the radius of bending of the conductor is increased, so the amount of strain in the wires is reduced. Second, the bearing pressures between conductor strand layers are reduced, thus reducing potential conductor internal strand damage. (This is commonly known as strand notching). Lined blocks are recommended for use with composite conductors. The minimum stringing sheave diameter is 32*D*, where *D* is the diameter of the conductor. The recommended diameter for the 477-kcmil 3M Composite Conductor is 28 inches.

Also, for the 3M Composite Conductor as well as AAC and ACSR, the maximum tensile stresses are obtained by superposition of tensile (pulling tension during stringing) and bending stresses (bending around stringing blocks). If the addition of all stresses exceeds the Rated Breaking Strength (RBS), the conductor will be damaged. The relationship between RBS, bend diameter, and superimposed tension is illustrated in Figure 52. It shows that a 28" sheave can safely be used with the 477-kcmil conductor if the tension is less than 1000 lbs. Additionally, 36 inch diameter wheels should be used for the bullwheel-tensioner, and pulling less than 2000 lbs, for the same reason of minimizing bending strains in the conductor.

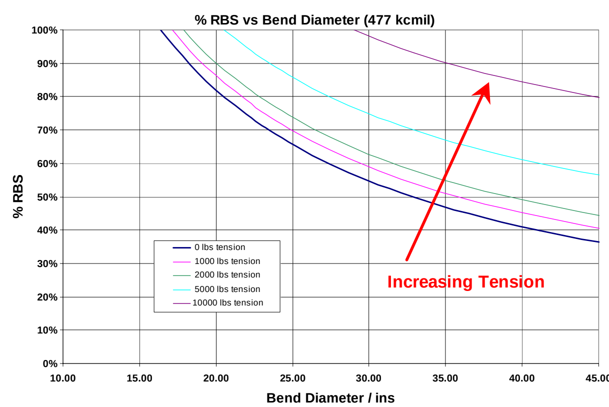


Figure 52: %RBS vs. bend diameter for 477 kcmil 3M Composite Conductor. Contours show how increasing applied tensions combined with bend diameters, increase the effective conductor loading (%RBS)

Quick Reference

Properties

A brief summary of 26/7 3M Composite Conductor behavior is shown in the following table.

Table of Properties

Property	Summary
Construction (for 26/7)	26 wires of temperature resistant Al-Zr alloy,7 wires of aluminum matrix composite
Test Span	Three years, survived 100 mile/hr winds (160km/hr)
Sag-Tension	Experiment validates Alcoa SAG10™ model. Sag predicted to ± 3 inches (75 mm) on a 770ft (235m) span. Aluminum layers have a compressive stress of -1.2 ksi (-8 MPa) at the transition temperature.
Ampacity-Temperature	Validates standard calculations for ampacity from IEEE, and CALITEM®.
Tensile Strength	Conductor exceeds the rated breaking strength.
Stress-Strain curves	Design coefficients derived
Creep	Very low. Predicted 10 year creep is ~0.04% at 30% RBS and 20°C. Creep coefficients derived. 10-year creep at 250°C <0.15%
Aeolian Vibration	Excellent resistance. Aluminum layers fail first.
Thermal Expansion	Low expansion. Meets prediction.
Electrical Resistance	Meets prediction.
Axial Impact Resistance	Excellent. Exceeds RBS under shock loads. Helical rod dead-end supports load.
Torsional Ductility	High ductility. Aluminum strands fail before core at 0.68 rot/ft (2.2 rot/m)
Crush Strength	Meets IEEE 1138 requirement – no damage, full strength retention
Short-circuit response	Runs cooler than equivalent ACSR conductor
Lightning Resistance	Damage levels equivalent to ACSR
Terminations & Joints	Alcoa-Fujikura compression style, and helical-rod assemblies from PLP. Hardware runs much cooler than conductor at high temperature, excellent mechanical properties
Suspension Assemblies	Helical-rod assemblies from PLP. Runs cool at high conductor temperatures, excellent mechanical properties.
Galloping	Excellent resistance. No damage
Dampers	Alcoa-Fujikura style. Use dampers at all times.
Installation Sheaves	Important to oversize sheaves-28 in (71cm) diameter. Full strength retention after sheave tests.
Installation Guidelines	Follow IEEE 524. Only use tension method, large blocks, swivels, sock splice, and only use preformed conductor grips to tension. Avoid tight radius requirements.

Accessories

A summary of accessories and their suppliers is shown in the following table.

Table of Accessories and Suppliers

Accessory	Alcoa-Fujikura	Preformed Line Products	Other
Dead-end	X	X	
Joint	X	X	
Jumper Terminal	X		
Jumper Connectors	X		
Tee Tabs	X		
Repair Sleeves	X	X	
Parallel Groove Clamps	X		
Dampers	X		
Spacers		X	
Sock Splice			X
Swivels			X
Grips		X	
Sheaves - Blocks			X

Questions/Contacts

For more information, design help, price quotes, and other information you can contact 3M directly.

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